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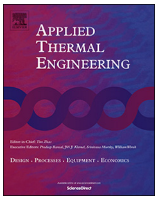

Research Paper

Flow structure and heat transfer of non-Newtonian fluids in microchannel heat sinks with dimples and protrusions

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HIGHLIGHTS

- Flow structures and heat transfer of CMC in a microchannel are investigated.
- Dimples/protrusions are vertically arranged on the opposite walls of a microchannel.
- Heat transfer enhancements are observed in all the cases studied.
- New correlations of f/f_0 and Nu/Nu_0 are present with a well-established data fitting.

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ABSTRACT

The flow structures and heat transfer of non-Newtonian fluids in a novel kind of microchannel heat sinks with dimples and protrusions were numerically investigated. The dimples and protrusions with a relative depth of 0.2 were vertically aligned to arrange on the opposite walls of the microchannel. The flow rate ranged from 3.72E–5 $kg{\cdot}s^{-1}$ to 8.69E–5 $kg{\cdot}s^{-1}$. The Fanning friction factor, form drag, frictional resistance, Nusselt number and thermal performance were analyzed to evaluate the overall thermal performance. Moreover, limiting streamlines and temperature distributions on the dimpled and protruded walls, as well as streamlines and dynamic viscosity distributions on the stream-wise middle sections, were used to investigate the effects of different parameters on the flow structure and heat transfer. New correlations of relative Fanning friction factor and Nusselt number were also proposed. It is shown that the heat transfer is enhanced, and the concentration of non-Newtonian fluids, flow rate and dimple/protrusion geometry have obvious combined effects on the flow structures and heat transfer. For the proposed microchannels, working substances with concentrations of 500 ppm and 2000 ppm are preferred.

1. Introduction

In many industries, such as the chemical engineering, power engineering, petrochemical engineering, pharmaceutical, biological, and food industries, it is usual to deal with the flow and heat transfer of non-Newtonian fluids. The flow of non-Newtonian fluids, especially shear-thinning fluids, in many microchannels, helical coil, and duct could produce heat transfer benefits with lower pressure penalty, thus strengthen the wholly thermal performance. So the non-Newtonian fluids attracted increasing attention in the heat transfer enhancement researches [1].

Prhashanna and Chhabra [2] numerically investigated the convective heat transfer of a horizontal cylinder in the quiescent power-law fluids, in which the flow and heat transfer behaviors of shear-thinning and shear-thickening fluids were studied. The results showed that shear-thinning fluids enhanced the heat transfer. Song et al. [3] numerically investigated the drag of a sphere in the Poiseuille flow of shear-thinning power-law fluids in cylinder vessels, and the results showed the wall had less influence in power-law fluids and the flow separation and separation zones were affected by confining wall. Singh et al. [4] conducted experiments and numerical analysis of the hydrodynamic of non-Newtonian fluid flow in their proposed novel coiled flow inverter, in which CMC (Carboxyl Methyl Cellulose) aqueous solutions were selected as the working substances, and the effects of flow rate, geometry and concentration of CMC on the frictional pressure drop were discussed in detail. Barkhordari and Etemad [5] numerically investigated the slip flow and thermal fields of non-Newtonian fluids in microchannels. The increasing slip coefficient resulted in increase of local Nusselt number, and this effect was enhanced as power law index increases.

Daniel and Dhiman [6] numerically studied the mixed-convection flow and heat transfer of non-Newtonian power-law fluids over

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circular cylinders, in which the drag coefficients and average Nusselt number at different cases were obtained and compared. The results showed that the aiding buoyancy and shear-thinning behavior enhanced heat transfer, even increasing by 85%, and then a heat-transfer correlation was obtained. Tso et al. [7] theoretically investigated the heat transfer of laminar thermally and hydrodynamically fully developed non-Newtonian fluids between parallel plates, and the results showed flow behavior had great effect on the heat transfer performance, while the thermal performance of shear-thinning and shear-thickening fluids differed much. Sasmal and Chhabra [8] numerically studied the laminar natural convection flow and heat transfer of a square cylinder submerged in static power-law fluids. The results showed heat transfer enhancement was obtained in shear-thinning fluids cases, even increasing by 100%, while not observed in shear-thickening cases. The friction factor and heat transfer of fully developed laminar non-Newtonian flow in a helical coil were experimentally studied by Primenta and Campos [9]. The results showed that the friction factors of CMC solution were lower than Newtonian fluids and other non-Newtonian fluids studied. Pawar and Sunnapwar [10] experimentally studied the isothermal steady and non-isothermal unsteady Newtonian and non-Newtonian flow in coils, and obtained several correlations based on the heat transfer data. The non-Newtonian behavior and resulting flow variations in the passage make the flow and heat transfer different with that of Newtonian fluids, and heat transfer enhancement could be also obtained in many conditions.

Due to the large convective heat transfer coefficient and high surface-area to volume ratio, microchannel heat sink becomes a useful method for high-efficiency heat and mass transfer [11]. Lee et al. [12,13] conducted experimental and simulation researches about the flow and heat transfer of microchannel heat sinks and obtained the local Nusselt number correlation. Flow control technologies have been introduced in the microchannels to achieve higher heat transfer enhancement, and the results showed strip-fins [14], wavy microchannel [15] and dimples/protrusions [16,17] were be beneficial, especially the dimples/protrusions [18]. Dimples and protrusions are useful for heat transfer enhancement with low pressure penalty in micro and mini-channels. The studies of heat transfer performance of minichannel with dimples showed the heat transfer coefficients increased to some extent [19,20]. Wei et al. [21] numerically studied the heat transfer enhancement of a microchannel with dimples for the first time, and the formation and development of separation flow and secondary flow in the passage were discussed, moreover, the pressure drop was indentified to equal to or less than that of smooth microchannels. Xie et al. [22] numerically investigated the thermal performance of water in microchannels with grooves and obstacles in the laminar region. The results showed the combination structures of grooves and obstacle were beneficial for heat transfer enhancement and the relative Nusselt number was from 1.45 to 26.19.

The previous works show that dimples/protrusions are effective heat transfer enhancement methods for microchannels. The authors [23] numerically investigated the laminar forced flow and heat transfer of nanofluids in a microchannel with dimple and protrusion, and the detailed flow structures and performance parameters varying with physical properties and geometrical structures were analyzed, finally the correlations of friction factor and Nusselt number were obtained. Furthermore, Zhang et al. [24] experimentally studied the thermal performance and friction characteristics of non-Newtonian fluids in regular rectangular channels with dimples and protrusions, in which xanthan gum solution, Carbopol 934 solution and polyacrylamide solution were selected as working substances. As was shown in the results, the combination of xanthan gum solution and dimple/protrusion gave rise to the heat transfer enhancement.

The non-Newtonian fluids and dimples/protrusions have advantages in heat transfer enhancement individually. The previous results also indicate that it's promising to apply the combination of non-Newtonian fluids and dimples/protrusions for heat transfer enhancement in microchannel heat sinks. Therefore, the laminar flow structures and heat transfer characteristics of non-Newtonian fluids (CMC aqueous solution) in the microchannel with dimple and protrusion vertically aligned to arrange on the opposite walls with a relative depth of 0.2 were analyzed in detail in this research.

2. Numerical methods and validation

2.1. Governing equations

In this study, CMC aqueous solutions, power-law non-Newtonian fluids, are selected as working substances. All physical properties used herein are consistent with previous literature [25–27]. The cases studied are steady-state laminar flow, so the continuity equation, momentum equations (taking X-direction for example), and energy equation are as follows [1,28,29].

$$\frac{\partial U}{\partial x}+\frac{\partial V}{\partial y}+\frac{\partial W}{\partial z}=0 \tag{1}$$

X-momentum

$$\rho\left(U\frac{\partial U}{\partial x}+V\frac{\partial U}{\partial y}+W\frac{\partial U}{\partial z}\right)=\frac{\partial \tau_{xx}}{\partial x}+\frac{\partial \tau_{yx}}{\partial y}+\frac{\partial \tau_{zx}}{\partial z} \tag{2}$$

Energy equation

$$\rho C_p\left(U\frac{\partial T}{\partial x}+V\frac{\partial T}{\partial y}+W\frac{\partial T}{\partial z}\right)=\lambda\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right) \tag{3}$$

where τ_{ij} is the viscous stress tensor, and subscripts *i* and *j* represent the normal direction of action surface and direction of stress component on the aforementioned surface, respectively. *U*, *V*, and *W* denote velocity components in the *x*, *y*, *z* directions, *T* and *P* are the fluid temperature and pressure, respectively.

The rheological behavior of the power-law fluid is represented by the following equation

$$\tau_{ij}=\eta\varepsilon_{ij} \tag{4}$$

where ε_{ij} is the rate of deformation tensor. In addition, η, the non-Newtonian fluid viscosity, is defined as follows for power-law fluids

$$\eta=K\left(\frac{I_2}{2}\right)^{\frac{n-1}{2}} \tag{5}$$

where I_2 is the second invariant of the rate of deformation tensor, *n* is the flow behavior index and *K* is the consistency index of CMC aqueous solutions.

Furthermore, Reynolds number and Prandtl number for non-Newtonian fluids [1,30] are defined as

$$\mathrm{Re}=\frac{D_h^n U_{ave}{}^{2-n}\rho}{K} \tag{6}$$

$$\mathrm{Pr}=\frac{CK}{\lambda}\left(\frac{U_{ave}}{D_h}\right)^{n-1} \tag{7}$$

where U_{ave} is the averaged velocity of inlet, and D_h is characteristic length. ρ, *C*, and λ are the fluid density, fluid specific heat, and fluid thermal conductivity, respectively.